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RESULTS OF THE STABLE MICROGRAVITY VIBRATION ISOLATION FLIGHT EXPERIMENT

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This paper presents an overview of the STABLE microgravity isolation system developed and successfully flight tested in October 1995. A description of the hardware design and operational principles is given. A sample of the measured flight data is presented, including an evaluation of attenuation performance provided by the actively controlled electromagnetic isolation system. Preliminary analyses of flight data show that the acceleration environment aboard STABLE's isolated platform was attenuated by a factor of more than 25 between 0.1 and 100 Hz. STABLE was developed under a cooperative agreement between National Aeronautics and Space Administration, Marshall Space Flight Center, and McDonnell Douglas Aerospace. The flight hardware was designed, fabricated, integrated, tested, and delivered to the Cape during a five month period.

INTRODUCTION

NASA, academic, and commercial consortia are all planning on-orbit microgravity experimentation and research activities aboard virtually all manned spacecraft, including shuttle (STS), Mir, and International Space Station (ISS). These activities include investigations into protein crystal growth, semiconductor fabrication, combustion, and fluid mechanics. The designers of many of these sensitive microgravity payloads are anticipating extended quiescent periods, of up to 30 days duration, during which experimentation will be carried out undisturbed by base acceleration or "g-jitter."

Mechanical disturbances from crew activities, onboard equipment, acoustics, ventilation, thermal creaking, and other sources threaten to disrupt the microgravity environment for these sensitive payloads, which could reduce scientific return or production quality. Figure 1 compares the predicted vibration environment aboard ISS with the desired environment. Note that ISS analytical predictions do not include vibrations induced by fluid flow, air currents, ventilation, acoustics, experiment equipment (such as pumps, fans, switches, valves), and thermal "creak." Although crew disturbances are simulated, no means exist to control crew activities. Many of these disturbance sources are especially significant at lower frequencies, where the

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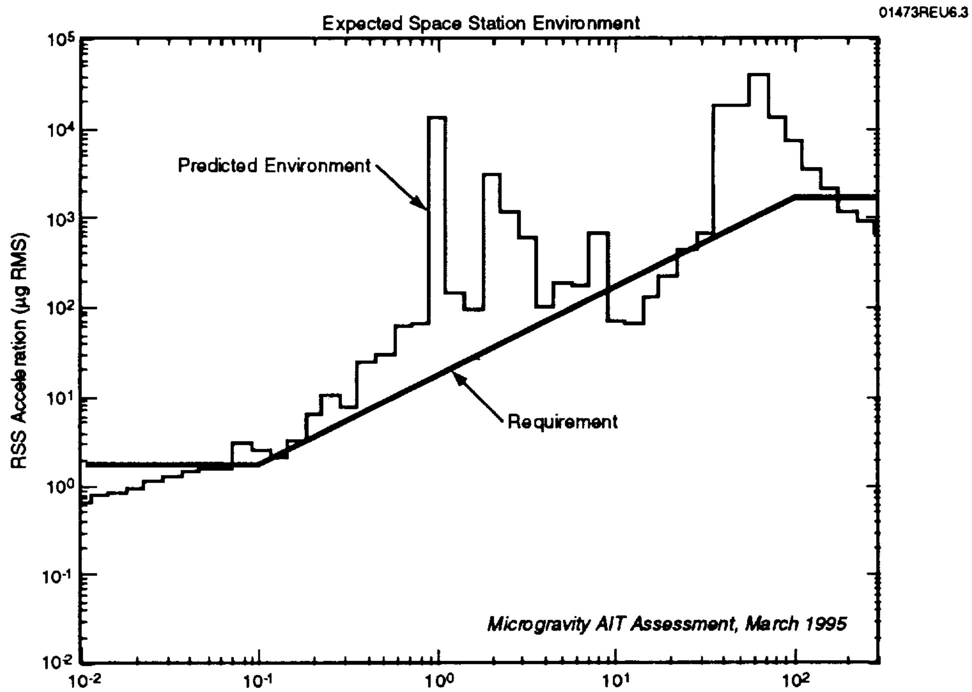

Figure 1. Vibration Environment Predicted for the International Space Station

microgravity requirement is the most demanding. One solution to this problem is vibration isolation.

With these disturbances in mind, over the past five years, McDonnell Douglas Aerospace (MDA) has pursued an independent research and development program on vibration isolation. Beginning in early 1995, MDA teamed with Marshall Space Flight Center (MSFC) to jointly develop the STABLE (Suppression of Transient Acceleration By LEvitation) isolation system. This effort culminated in the world's first flight of an active microgravity vibration isolation system on STS-73/USML-02 in late 1995. The STABLE isolator can prevent unwanted disturbances from reaching critical scientific and commercial payloads and provide environments in the 10^{-6}g (1 μg) range.

ISS management has determined that an actively controlled isolation system will be necessary to meet the requirement shown in Figure 1, and has baselined the Active Rack Isolation System (ARIS) to isolate 50% of the US allocation of International Standard Payload Racks to be flown on ISS. The STABLE system provides an alternate, complementary vibration isolation system that could help NASA provide the required microgravity levels and may also be applied to microgravity payloads to be flown by international partners in ISS, as well as Mir, shuttle, and SPACEHAB.

STABLE HARDWARE DESCRIPTION

The STABLE system provides component-level isolation as an alternative to the rack-level approach. The concept of isolating only the vibration-sensitive portion of a payload minimizes the number and size of any utility umbilicals, since the floating portion of the payload is not necessarily connected to all on-board support systems. In multi-experiment racks, it also protects each individual payload regardless of disturbances produced by nearby experiments, including crew servicing activities. Component-level isolation also eliminates the potential for disturbances due to accidental crew contact with the rack or its enclosure.

The STABLE hardware, in the configuration successfully flown on STS-73, is shown in Figure 2. STABLE provided an uninterrupted microgravity environment for a fluid dynamics experiment dubbed "CHUCK." Both experiments were contained within a single middeck locker container. In addition to providing a microgravity environment to the on-board experiment, STABLE transferred power, data, and video signals to the platform by flexible umbilical cables. The platform and CHUCK were levitated by three MDA dual-axis wide-gap electromagnetic actuators.

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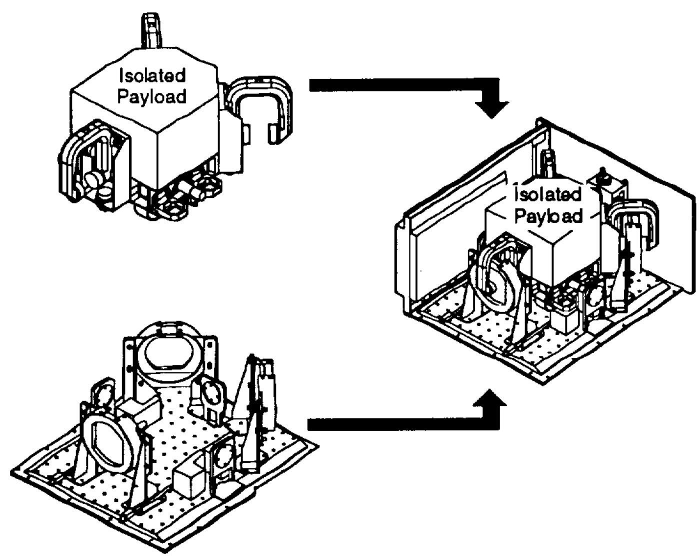

Figure 2. STABLE Physical Layout

STABLE isolates by floating a platform on electromagnetic actuators that apply forces to counteract those that are transmitted through umbilicals or that originate within the experiment itself. Accelerations caused by these disturbing forces are measured by accelerometers on the platform, and these signals are used by a high bandwidth feedback controller to command the counteracting actuator forces. In addition to the acceleration controller, there is a very low bandwidth position loop that tends to keep the platform centered. Signals from three, two-axis optical sensors measure the position of the

platform with respect to the base and are used to maintain centering. The centering function compensates for the extremely low-frequency disturbances for which adequate rattle space cannot be provided. This topography is depicted in Figure 3.

The STABLE actively controlled vibration isolation system suspends its sensitive payload and tries to keep it totally still and motionless, even though it is surrounded by and connected to a vibrating spacecraft. The only way disturbances can make their way from the outside to the sensitive payload is through the service umbilicals. For this reason and to minimize power consumption, the umbilicals must be made as flexible as possible. For optimum performance, the umbilicals should have zero stiffness, but this is not possible with real payloads requiring power, data, fluid, or vacuum needs.

The innovative STABLE approach to vibration isolation is to utilize the field-proven, MDC-patented stabilized platform technology. This technology is currently being used to provide precision microradian-accuracy stabilization in the extreme vibration environment above helicopter rotors. In this program, the optical platform carries sensitive sighting apparatus and is stabilized by compact, efficient, dual-axis, non-contacting electromagnetic actuators. The positioning and control hardware used was directly applied to the task of microgravity vibration isolation. Each actuator provides two directions of full actuation authority over ±1 cm of free travel in all three directions as shown in Figure 4. This free travel allows the payload to "sway" and achieve its microgravity performance.

The paddle-shaped armature of the actuator (circular shape in Figure 4) is mounted to the frame of STABLE's support structure so that conduction may be used to dissipate any heat generated, and actuator wiring does not need to be carried over the umbilicals. The horseshoe-shaped permanent magnet carriers are mounted on the floating platform, and are arranged so that they overlap the armatures (see Figure 2 for arrangement details).

Although the STABLE isolated platform is allowed to move freely during normal operation, for safety reasons it must be secured for events such as launch, reentry, and landing. An innovative lockdown system was designed to secure the platform during these periods as well as whenever it was not operating. The lockdown mechanism consisted of four inverted V-shaped cones and specially shaped eyelets mounted on the floating platform. To secure the floating platform, the cones were pulled downward toward the base of the container to a fixed preload value. The shaping of the cones was such that when they came into contact with the eyelets, the platform would automatically be centered before the preload was applied. This unique mechanism was activated by a single motion of a lever on the front of the STABLE container.

CONTROL SYSTEM DESCRIPTION

The key to the robust performance of STABLE is its six independent position and acceleration loops. This unique, MDA patent-pending system provides very high bandwidth acceleration feedback along with a positioning system that is insensitive to drift. The hierarchy of this system is shown in Figure 5.

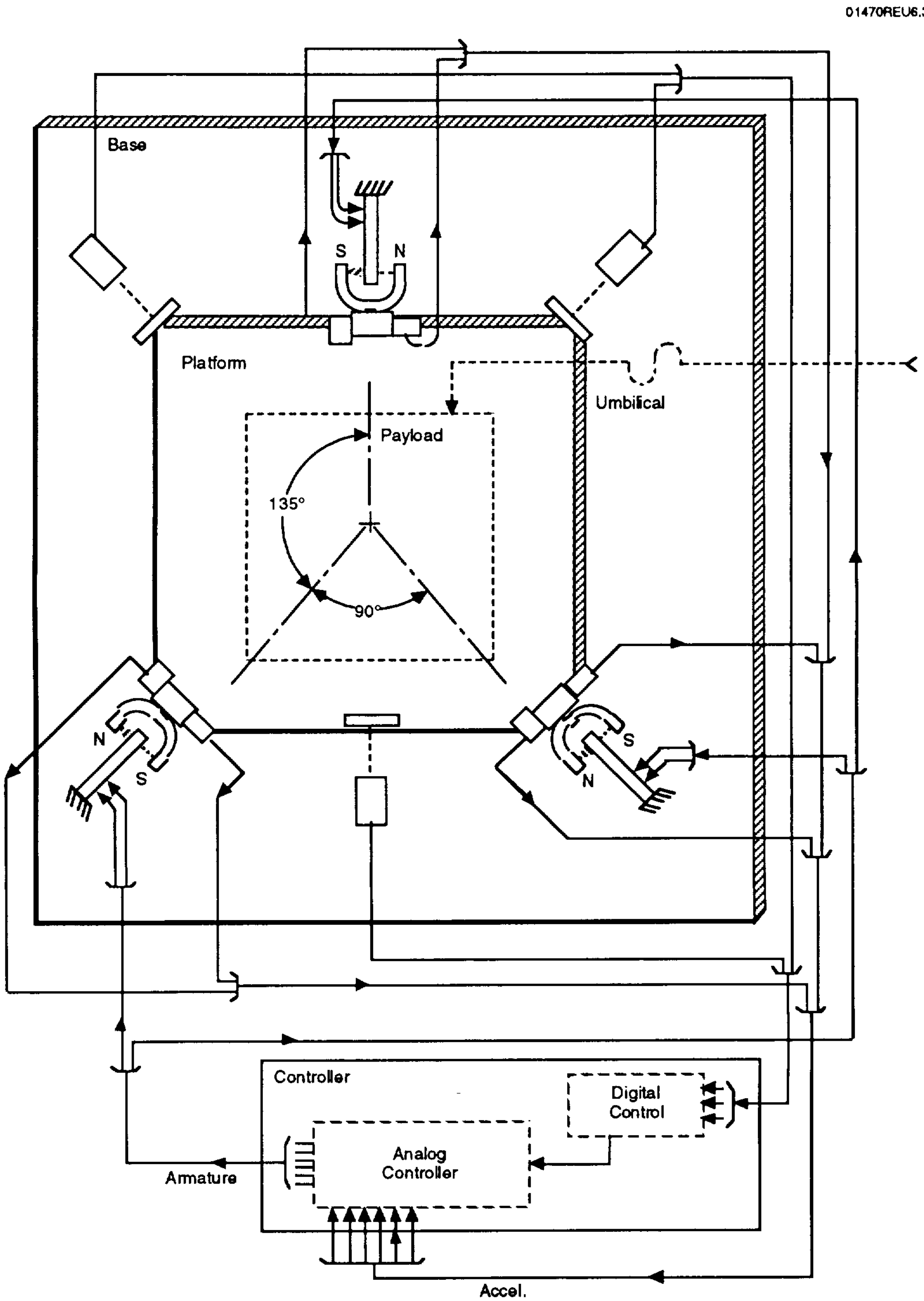

Figure 3. STABLE Functional Diagram

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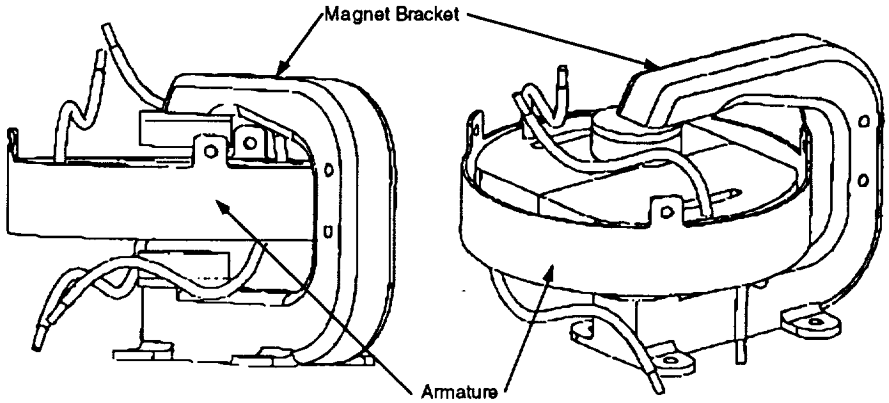

Figure 4. MDA Dual-Axis Actuators

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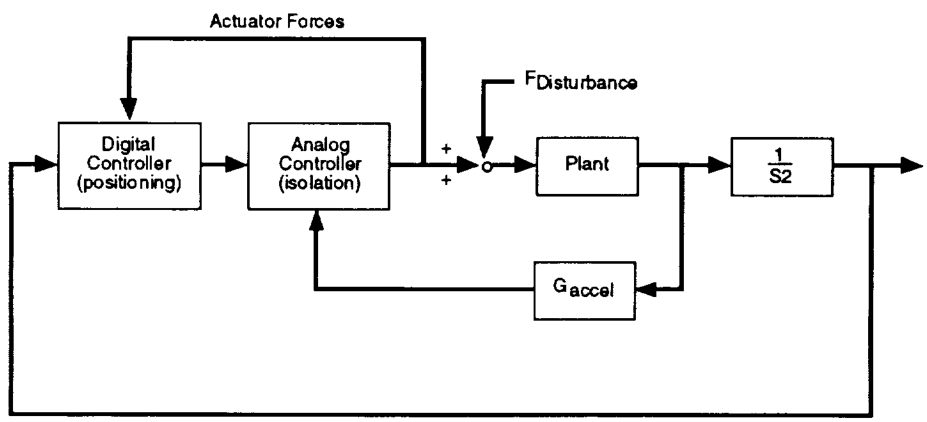

Figure 5. STABLE Control System Architecture

The patent-pending STABLE control system consists of six independent channels. The digital controller uses position data generated by light from a set of small lasers (mounted on an isolated platform) shining on targets (mounted on the base) to compute the six-degree-of-freedom (6-DOF) displacement of the floating platform, and very gradually recenters the floating platform over a period of minutes. The analog controller is a 50-Hz bandwidth system using an accelerometer to measure the platform's absolute acceleration, which is processed and fed to the actuators to null the acceleration.

In order to provide a quiescent inertial environment for the isolated platform, the

isolation system must provide a soft suspension with respect to base motion disturbances, while providing a stiff suspension with respect to inertial (directly transmitted) disturbances. These competing objectives cannot be attained with passive isolation alone, but require active isolation with inertial acceleration feedback.

Acceleration Controller

The analog acceleration controller, shown in the center of Figure 5, attempts to cancel acceleration disturbances as sensed by the accelerometers. The analog accelerometer measurement forms the acceleration error signal input to the analog acceleration controller. A rate feedback-type acceleration controller provides stability robustness since the actuator and sensor are spatially colocated. A low-pass filter provides roll-off at a nominal bandwidth of 50 Hz. Performance of the acceleration loop is limited by controller bandwidth, accelerometer noise, resolution- and temperature-dependent bias variations, and disturbances transmitted through the umbilical connections. The output from the acceleration loop is the current command to the actuator coils.

The STABLE high-frequency analog controller is impervious to single-event upsets (SEUs) caused by radiation while in orbit. As a result, the STABLE configuration is likely to suffer far fewer upsets, with corresponding better performance. The same cannot be said for isolation systems using digital controllers for their high-bandwidth control schemes. Analysis shows that STABLE would suffer a single-event upset once every 27 years.

Position Controller

A vibration isolator must attenuate "high-frequency" vibrations and be able to move with respect to the support structure and thus maintain an inertial position (or velocity) while the surrounding structure is in motion. To accomplish this, space must be provided around the isolated structure for it to "sway" back and forth. The geometry of the sway space determines the lower frequency limit for attenuation of base motion. Below this low-frequency limit, quasi-steady forces must be transmitted to the platform so that the platform will follow the low-frequency motion of the support structure. On STABLE, the position controller serves this purpose.

The position loop is a digital PID controller which uses position measurements to compute the position of the actuator with respect to a nominal centered position. Since the position sensors are not coincident with the actuators, they do not provide a direct measure of displacement in the input axis of the accelerometer, and additional computations are performed in the digital processor to determine the position errors at the actuator gap. Once computed they are passed to the position controller, also in the digital processor, which calculates acceleration commands to each actuator. These are summed with the accelerometer signals and form the input to the acceleration loop control law.

The position control law operates in either of two modes depending on the calculated actuator gap. While the gap position error is small, low PID gains are used to provide a very small restoring force which will not violate the acceleration requirements. If the gap

error becomes large (meaning the platform is nearing the boundaries of its sway space), a set of high gains effectively increases the spring constant of the control law to prevent the platform from making mechanical contact.

Structural Dynamics Considerations

The performance of an isolation system is determined by the amount of gain that can be employed. Flexibility in the support structure can force a reduction in gains that in turn limits performance. For this reason, STABLE was designed to have a high-stiffness platform such that the first free-free structural vibration mode is well over 200 Hz. The stiffness of the STABLE platform allows high system feedback gains and enhances performance.

In addition, since the STABLE isolation scheme can be tailored to only isolate the critical portion of an experiment, it will not be subjected to external disturbances that might appear on external faces of experiment racks such as those generated by acoustical, ventilation, and crew motion.

EXPERIMENT OBJECTIVES

The objective of STABLE was to demonstrate vibration isolation on-orbit with an operating scientific experiment, while passing power, data, and other services over a service umbilical. We hoped to meet the ISS microgravity requirements (Figure 1) during flight testing. Because on-orbit power is a very scarce resource, we hoped the STABLE hardware would consume less than 100 watts average electrical power during isolation operation in an active but "quiescent" shuttle environment (vigorous astronaut activities but no thruster firings).

This type of information cannot be obtained by ground testing. A six-axis ground test is not feasible because available low-frequency suspension systems possess stiffnesses large enough to completely wash out the μg inertial forces on the isolated payload. A ground suspension system supporting a 20-kg mass would simultaneously have to support a weight of about 200 N while having a dynamic resistance force much smaller than 0.002 N (one-millionth of its weight, a force about one-twentieth of the weight of a sheet of ordinary paper). No known active suspension systems can deliver this performance. In addition, there are no known ways to suspend umbilicals so that they achieve the same shape and preload as they would in microgravity or to effectively simulate three-dimensional orbiting disturbances.

FLIGHT MEASUREMENTS

The STABLE flight demonstration included measurements of the isolated payload's acceleration and position, base acceleration, actuator currents, accelerometer temperature, and control system gain settings for system performance evaluation. All data recording for the science payload was also incorporated into STABLE, with the exception of video signals which were transmitted across the STABLE umbilical and recorded separately.

STABLE was designed for autonomous operations with minimal astronaut attention and little or no feedback concerning operation or data gathering. It used a PGSC-486 laptop as a data acquisition system for the on-orbit measurements. Two 12-bit analog-to-digital Personal Computer cards (PC-cards) were connected via a data cable. Crew members simply activated STABLE and the PGSC, and measurements were recorded to an 11-Mbyte RAM disk, which was periodically copied on to the hard drive in the PGSC. Each hard drive held 500 Mbytes of data, covering a time period of about 12 hours. During operation, a crew member changed hard disks twice daily. A total of about 72 hours of data (3.5 Gbytes) was recorded on-orbit.

The data acquisition system sampled and recorded data from all accelerometers at a rate of 250 samples per second. This provided data on system behavior at frequencies up to a theoretical maximum of 125 Hz, although in practice frequency data above about 50 Hz is considered less reliable. All of these signals passed through a 130-Hz filter to eliminate aliasing effects. A longer sampling period, 10 samples per second, was used for slowly varying quantities as accelerometer temperature.

The acceleration sensor used was the AlliedSignal QA-2000. This accelerometer provides μg performance in a relatively inexpensive package; it is the industry standard for monitoring microgravity accelerations on board the shuttle. STABLE performance is directly limited by the accelerometer noise floor, which is shown in Figure 6. The predicted noise levels are low enough to permit STABLE measurements to be compared with Space Station requirements, but they are still significant relative to the absolute acceleration accuracy desired for the platform measurements.

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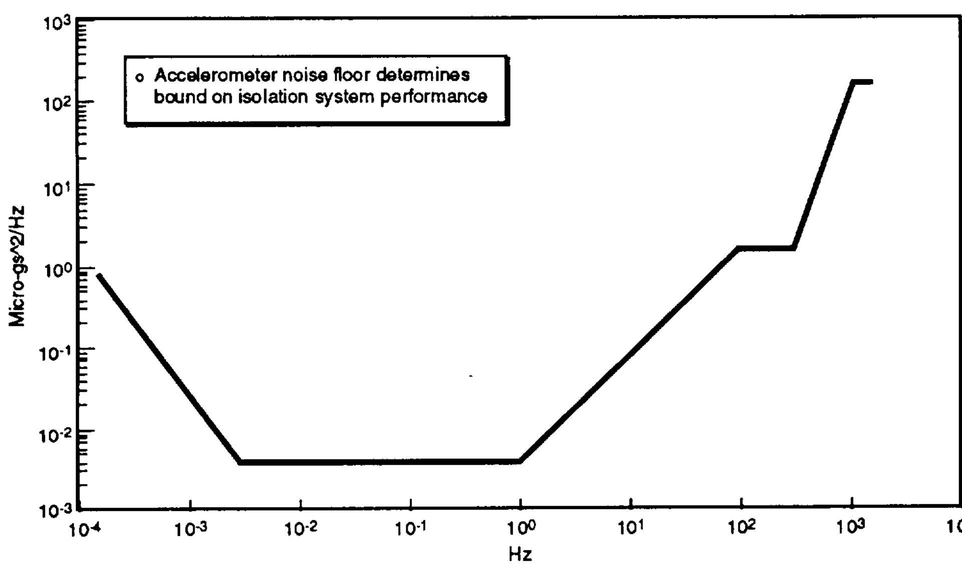

Figure 6. QA-2000 Accelerometer Noise Envelope

Three accelerometers were located on the frame of the STABLE locker box as shown in Figure 7. These channels provided a reference signal for the determination of isolation performance. Six accelerometers were located on the floating platform, colocated with the actuators as shown in Figure 7. Initial postprocessing transformed the six platform acceleration measurements to six components of motion at the approximate platform center of gravity.

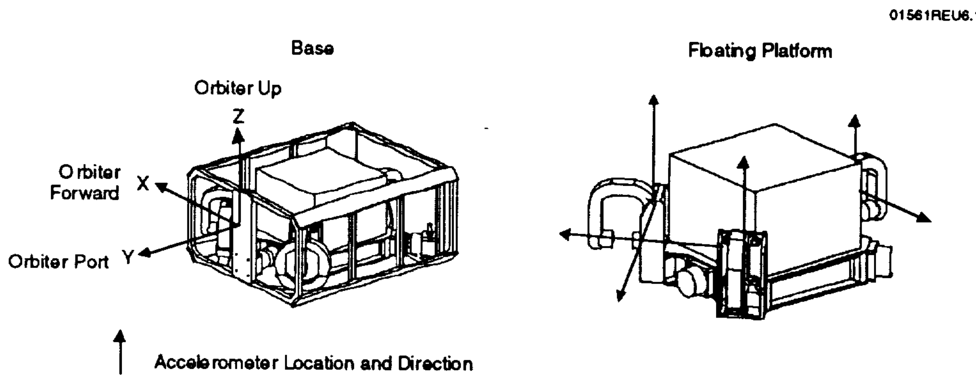

Figure 7. Accelerometer Coordinate Systems

Once transformed into parallel coordinates, the three translational components of acceleration from the locker box frame and experiment platform were processed to yield a variety of isolation system performance measures. These include time history, RMS, histogram, power spectral density, cumulative power spectral density, transfer function, and one-third octave RMS average. The last format is used to compare STABLE performance with the current Space Station program requirements.

The preliminary frequency domain data presented here was processed using standard windowing and averaging techniques. The total time history for each data block was separated into 15 ensembles, adjusted to zero mean, and windowed using the power-corrected Hanning method before transformation into the frequency domain. Fast Fourier transforms were performed with 8192 points, yielding spectral data down to 0.03 Hz. As a check, total power in the time and frequency domain signals was compared and verified to be essentially the same.

During the course of the flight, the astronauts provided various force inputs to the shuttle by pushing off a wall, typing on a console, closing a locker door, doing exercises, and performing other actions. Orbiter vernier thrusters were fired every few minutes and primary thrusters were fired several times per day. Other events such as water dumps and payload bay door operation were also captured in the STABLE data. Unfortunately, STABLE was not able to access the Orbiter time reference system; instead, approximate mission time was recorded by a crew member during the changeout of each STABLE hard drive. Thus, these events can be only approximately located in the data prior to processing. It is expected that special techniques such as band-pass filtering will be

required to accurately identify particular events. The preliminary data presented here is a randomly chosen block of data and does not represent any known special event.

The simplest performance measure is an acceleration time history plot (Figure 8). The vibration levels aboard STABLE's isolated platform are almost invisible compared to the ambient vibration levels measured. The base acceleration trace shows instantaneous accelerations as high as 3000 μg, while the isolated platform acceleration is more than 30 times less throughout the duration of the sample. Figure 9 shows a close-up of both the base and platform time histories.

Histogram plots of the time history data are useful for identifying several common data acquisition problems (such as sensor saturation) if they are present. As shown in Figures 10 and 11, the STABLE data appears to be stationary random with an approximately Gaussian distribution, as expected. The RMS value of the base and isolated signals, shown with vertical lines in Figure 11, are another useful performance measure. During this period, total power was reduced by a factor of about 17.

The power spectral density curves in Figure 12 show that STABLE's isolation system performed well across a wide frequency spectrum. While the results are still preliminary and extensive correlation with known disturbances has not yet been done, some features are rather easily recognizable. High-frequency line spectra are evident on the locker box

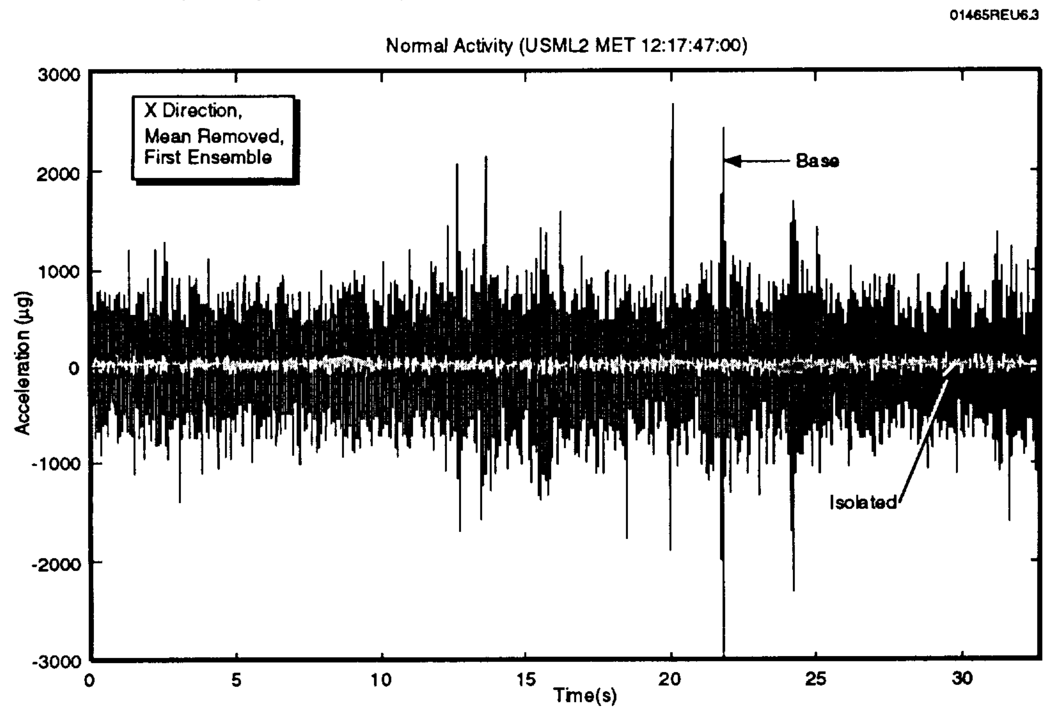

Figure 8. Base and Isolated Acceleration Time History

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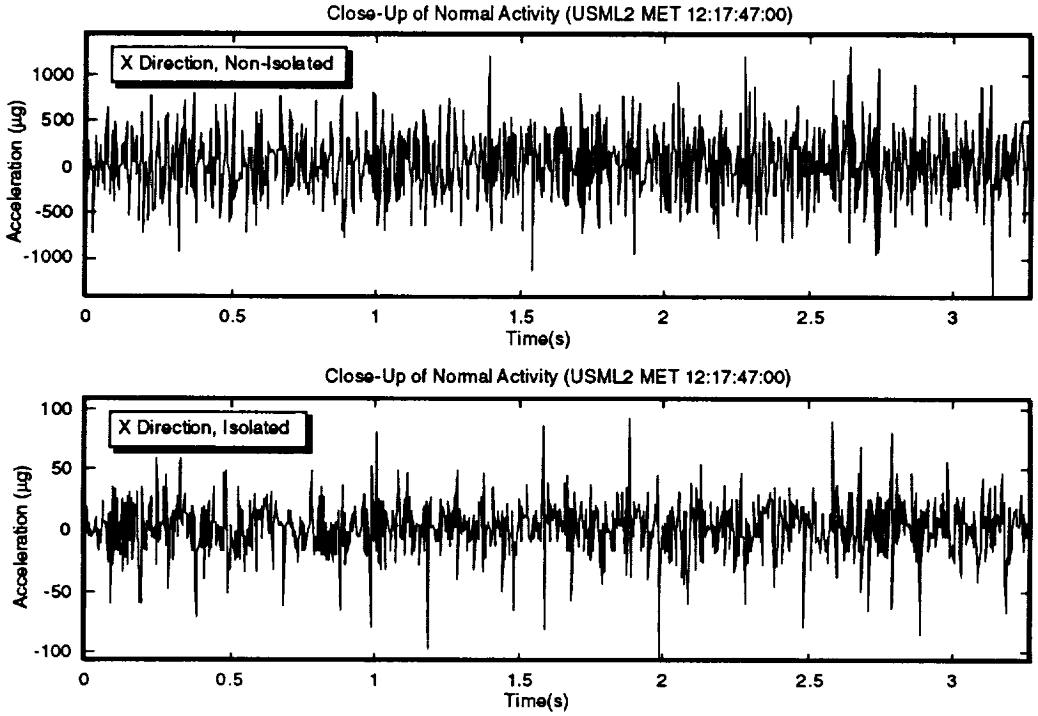

Figure 9. Expanded View of Acceleration Time History

frame at 60 and 100 Hz, probably due to mechanical equipment in neighboring USML-2 experiments. The Orbiter's K_u-band antenna dither is clearly visible at 17 Hz. In general, the Orbiter environment has significant acceleration amplitudes across all frequencies shown.

The International Space Station has framed its vehicle vibration limits in terms of one-third octave frequency bands. This represents a power spectral density integrated over a bandwidth proportional to frequency, with the square root taken of the resulting integral to reduce the units to micro gs. As shown in Figure 13, the Orbiter environment does not meet this requirement in some low-frequency bands, but the isolated environment provides significant margin across all frequencies.

The isolated platform results shown in Figure 13 represent not only platform motion but include the contribution of several different noise inputs: accelerometer noise and noise due to aliasing and quantization. Hence the actual platform motion is less than that shown in the isolated curve. The noise contributions may be described by the following equations:

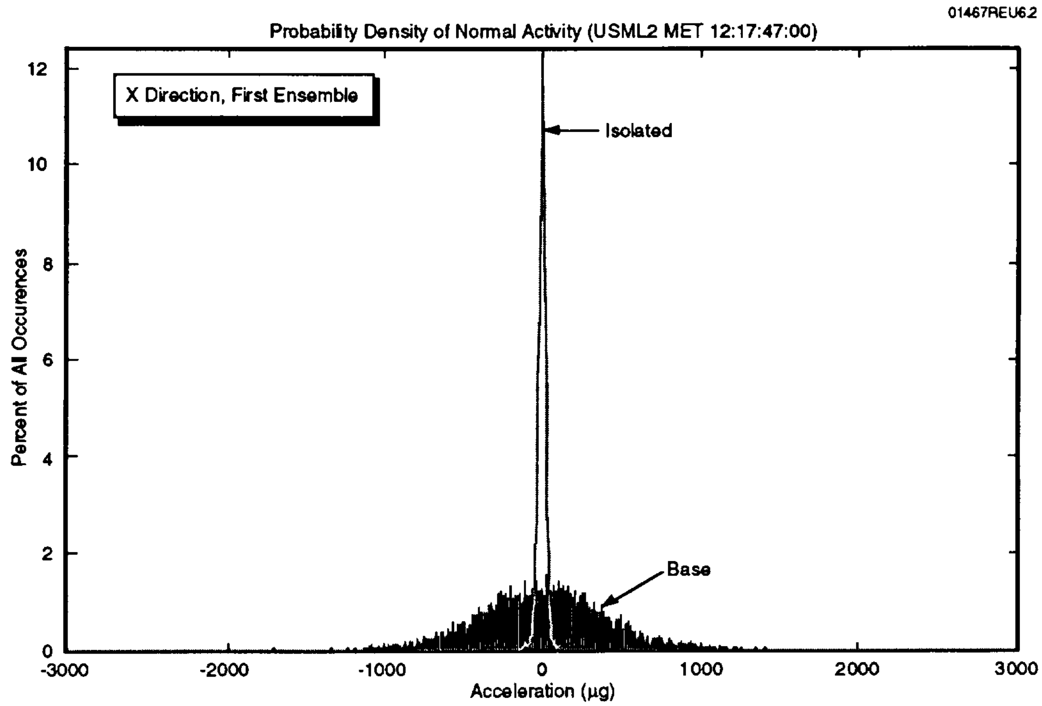

Figure 10. Base and Isolated Acceleration Histograms

$$\ddot{y}_{recorded} = \ddot{y}_{measured} + n_{alias} + n_{quant}$$

$$\ddot{y}_{measured} = \frac{Y_{measured}}{F_{umbilical}}(j\omega) \bullet F_{umbilical} + \frac{Y_{measured}}{n_{accel}}(j\omega) \bullet n_{accel}$$

$$\left|\ddot{y}_{recorded}\right|^2 = \left|\frac{\ddot{Y}_{measured}}{F_{umbilical}}\right|^2 \cdot \left|F_{umbilical}\right|^2 + \left|\frac{\ddot{Y}_{measured}}{n_{accel}}\right|^2 \cdot \left|n_{accel}(j\omega)\right|^2 + \left|n_{alias}(j\omega)\right|^2 + \left|n_{quant}(j\omega)\right|^2$$

Combining the manufacturer's accelerometer noise specification with the sampling errors resulting from quantization and aliasing (in effect zeroing the umbilical forcing term in the equation above), yields the bottom curve in Fig. 13. A higher sampling rate and better filter choices will provide further improvement.

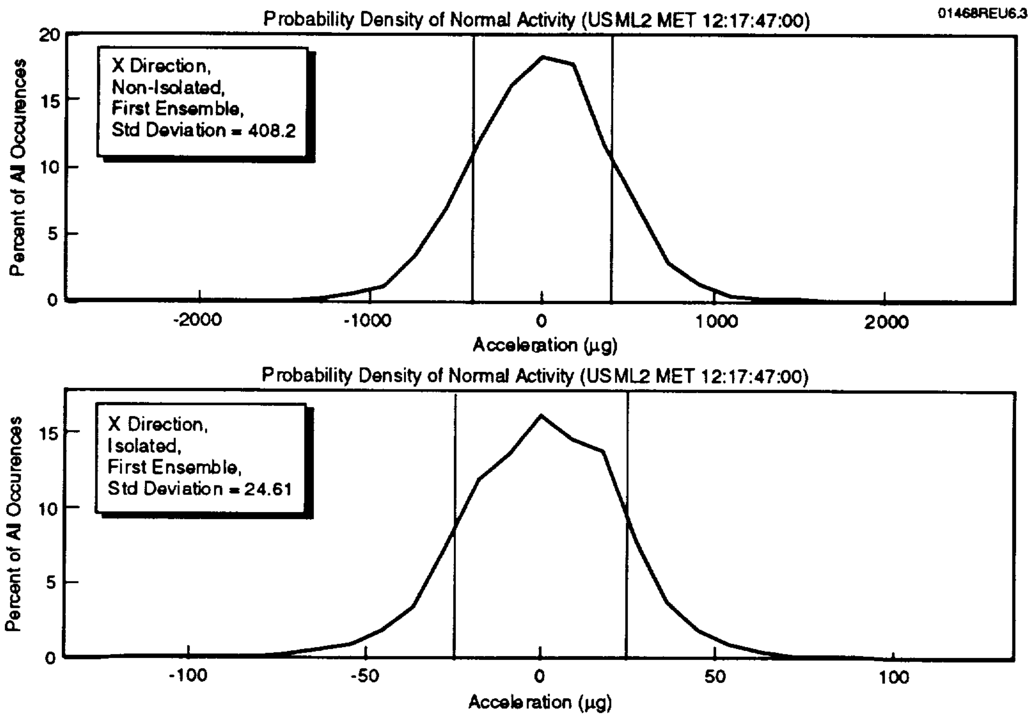

Figure 11. Expanded View of Acceleration Histograms

CONCLUSION

STABLE operated quite successfully with minimal crew attention and returned several gigabytes of both isolated and ambient acceleration and position measurement data. Based on preliminary examination of a small portion of flight data, it appears that the STABLE apparatus was able to provide substantial attenuation of disturbances on board the shuttle. Acceleration levels were reduced by an order of magnitude or more over the desired frequency range. The data analysis is continuing, and the recorded data are being searched in an attempt to locate the times during the flight with interesting acceleration data.

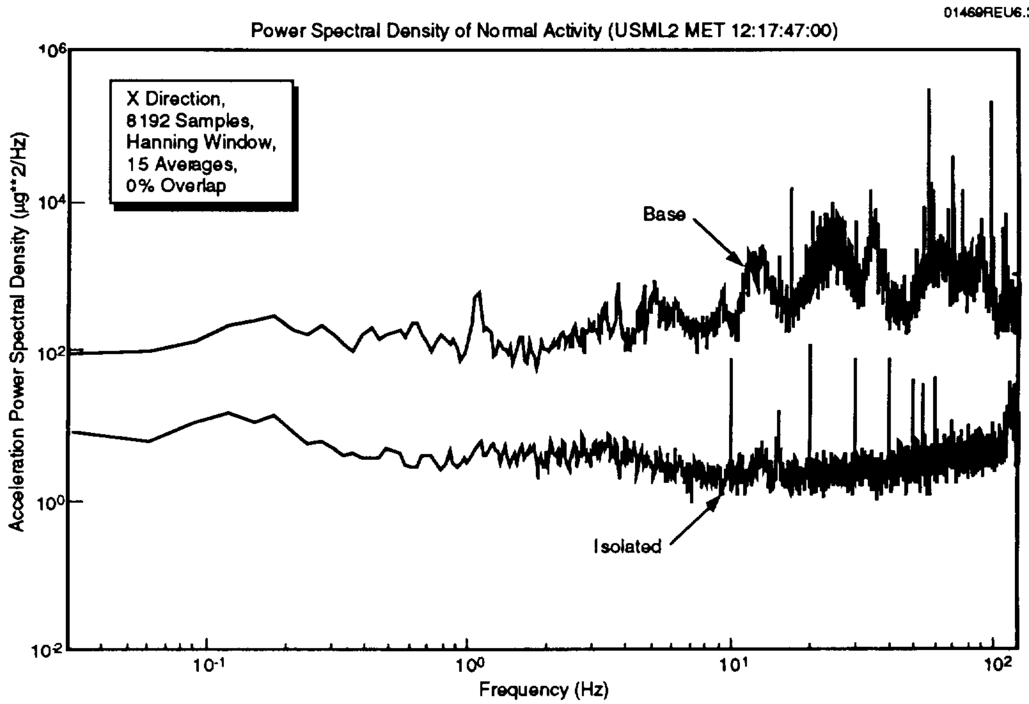

Figure 12. Base and Isolated Power Spectral Density

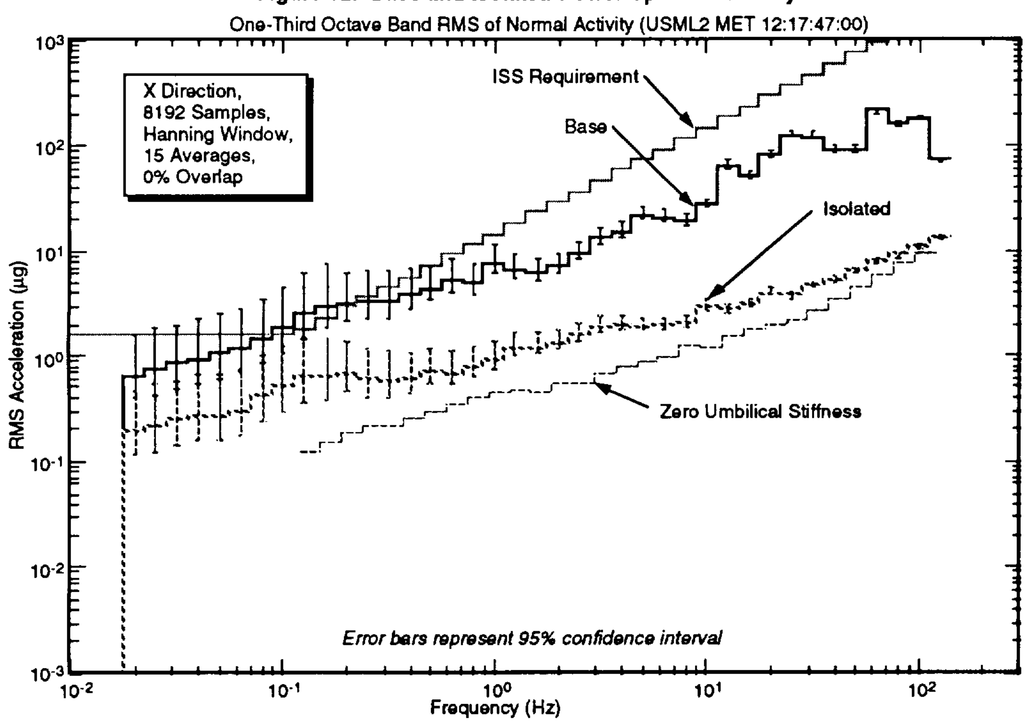

Figure 13. RMS Acceleration Averaged Over One-Third Octave Bands (revised)